UNCLASSIFIED

| AD NUMBER |
| --- |
| AD012912 |
| CLASSIFICATION CHANGES |
| TO: unclassified |
| FROM: restricted |
| LIMITATION CHANGES |
| TO: Approved for public release, distribution unlimited |
| FROM: Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; 04 MAR 1953. Other requests shall be referred to Naval Ordnance Lab., White Oak, MD. |
| AUTHORITY |
| E.O. 10501 5 Nov 1953; USNOL ltr, 29 Aug 1974 |

THIS PAGE IS UNCLASSIFIED

**NOTICE:** THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 and 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

# NAVORD REPORT 2737

DESIGN OF MAGNETIC CONTROL AMPLIFIER XM-13A

4 MARCH 1953

## U. S. NAVAL ORDNANCE LABORATORY

WHITE OAK, MARYLAND

~~RESTRICTED~~

SECURITY INFORMATION

# DESIGN OF MAGNETIC CONTROL AMPLIFIER XM-13A

Prepared by:

Herbert H. Woodson

ABSTRACT: The design of the magnetic control amplifier XM-13A to drive the azimuth, roll, and pitch systems of the Bomb Director AN/ASB-1 is described. In these systems two motors are used, the BuOrd Mark 12 and BuOrd Mark 15, 400-cycle servo motors. This control amplifier drives both motors with essentially the same dynamic characteristics. The final design of the control amplifier contains two half-wave, bridge-type, magnetic amplifiers having two stages each. One amplifier drives the motor and provides gain in the tachometer compensation loop while the other amplifier is used with positive integral feedback around it to give integrating action. The cascaded integrating network gives the system a zero velocity error.

U. S. NAVAL ORDNANCE LABORATORY
White Oak, Silver Spring, Maryland

NAVORD Report 2757 4 March 1953

The Bureau of Ordnance assigned to the Naval Ordnance Laboratory task NOL-Re8-1-2-53 of which one problem was to design magnetic control amplifiers for the Antenna of Bomb Director AN/ASB-1. This report describes the design of one type of amplifier to drive all the required systems within the dynamic specifications, but does not include engineering for temperature, voltage, and frequency variations.

EDWARD L. WOODYARD
Captain, USN
Commander

D. S. MUZZEY, Jr.
By direction



~~RESTRICTED~~
~~SECURITY INFORMATION~~

CONTENTS

| | Page |
|---|---|
| Introduction | 1 |
| System Specifications | 1 |
| Qualitative Design | 2 |
| Amplifier Design | 3 |
| Output Member | 3 |
| Integrator | 3 |
| Complete System | 4 |
| Conclusions | 4 |
| Acknowledgment | 5 |
| References | 7 |

ILLUSTRATIONS

| | | |
|---|---|---|
| Figure 1. | Block diagram of system | 8 |
| Figure 2. | Qualitative frequency response curves | 9 |
| Figure 3. | Schematic diagram of two-stage amplifier | 10 |
| Figure 4. | Details of magnetic cores | 11 |
| Figure 5. | Block diagram of output member | 12 |
| Figure 6. | Block diagram of integrating circuit | 13 |
| Figure 7. | Complete block diagram showing external parameter values | 14 |
| Figure 8. | Closed loop frequency response curves | 15 |

Table I .......... 6

# DESIGN OF MAGNETIC CONTROL AMPLIFIER XM-13A

## INTRODUCTION

1. The specifications on the magnetic control amplifier for the azimuth, roll, and pitch systems of the Bomb Director AN/ASB-1 are given in Table I. In addition, these specifications must be met using both the BuOrd Mark 12, 400-cycle servomotor and the BuOrd Mark 16, 400-cycle servomotor with a mechanical system that reflects an inertia to the motor shaft of approximately twice the motor inertia. The inertia of the motors are approximately the same; therefore, one simulated mechanical system can be used for both motors. The gear ratio between motor and control transformer is 1000:1. Standard BuOrd 400-cycle, 115-volt synchros are used for error detection.

2. Also shown in Table I are the performance characteristics of the magnetic control amplifier XM-13A which was designed for this application by the Magnetic Amplifier and Servomechanisms Group of the Magnetics Division.

### System Specifications

3. The dynamic error at constant velocity and the system bandwidth required by the specifications (see Table I) dictate that some type of compensation be used. The specification on package size requires that the compensation be accomplished by the method that is simplest and requires the least equipment. At the present time the simplest method of supplying compensation to the system is a half-wave, bridge-type, magnetic amplifier with integral feedback.[1] When this type of compensation is used, the simplest over-all system will be obtained when half-wave, bridge-type magnetic amplifiers[2] are used to obtain amplification in the system.

4. The gear ratio of 1000:1 requires an amplifier gain not normally obtainable with a reasonable number of cascaded half-wave stages. However, with lag or integral compensation added in cascade, the static gain can be increased to the proper value to meet the specifications; in fact, when integral compensation is used, the static gain is infinite.

5. This magnetic control amplifier must meet the AN-E-19 Air Force-Navy Aeronautical Specifications. Over the temperature, voltage and frequency ranges, the amplifier gain will change by a small amount. When, for the maximum gain condition, the system is designed for zero velocity error using the integral compensation described in reference (1), the compensation will become

lag compensation when the gain decreases. The change in gain must be made small enough that the dynamic specifications are still met with the lag compensation present at the minimum gain condition. The amplifier gain change will depend upon the care used in matching and selecting components.

## Qualitative Design

6. A zero-velocity-error system, designed in accordance with reference (1), will have the block diagram shown in figure 1. The open-loop transfer function of this system is

$$\frac{C}{E} = \frac{K(Tj\omega+1)}{T(j\omega)^2(T_m j\omega+1)} \qquad \text{Eq. (1)}$$

where $\omega$ is the signal frequency, T is the integrator time constant, $T_m$ is the output-member time constant, and K is the static gain. The constants will be derived below.

7. Referring to figure 1, when the integrator time constant, T, is larger than the output member time constant, $T_m$, the open loop function (equation (1)) will have the frequency response characteristic shown in figure 2(a) and 2(b). When the gain, K, is so adjusted that

$$\left|\frac{C}{E}\right| = 1 \qquad \text{Eq. (2)}$$

at the signal frequency

$$\omega = \frac{1}{\sqrt{T\ T_m}} \qquad \text{Eq. (3)}$$

and the loop is closed, the phase margin will be a maximum and the system will be most stable. If the maximum phase margin indicated in figure 2(b) is sufficiently large, the loop may be closed at any one of a range of frequencies above and below that given by equation (3) while maintaining adequate system stability.

8. The proof that maximum phase margin occurs at the frequency given by equation (3) lies in recognizing that the only portion of equation (1) with a frequency variant phase shift is

$$\frac{Tj\omega + 1}{T_m j\omega + 1} \qquad \text{Eq. (5)}$$

With the above stated relation between T and $T_m$, the function in equation (5) is a lead circuit, the characteristics and normalized frequency-response curves of which can be found

in any book on servomechanisms. Using such a set of normalized curves[3], the circuit parameters can be selected to give the phase margin desired at the proper frequency.

## Amplifier Design

9. From past experience, it was found that a practical system could be designed using two half-wave, bridge-type, magnetic amplifiers[4] having two stages each. The circuit diagram of the amplifier used is shown in figure 3, while the core details are given in figure 4. The requirements are one amplifier to drive the motor and supply gain for the tachometer compensation loop and one amplifier with positive integral feedback to form the integrator.

10. There are a number of restrictions placed on static performance of the amplifiers. The amplifier that drives the motor must, with full output, drive the motor sufficiently fast to meet the specification of maximum slewing rate. In addition, this amplifier must supply sufficient gain to the tachometer loop to provide proper compensation. The amplifier to be used in the integrator must have sufficient output in its linear range to override the tachometer voltage and drive the second amplifier to full output with the motor running at top speed.

## Output Member

11. The block diagram of the output member is shown in figure 5. The natural frequency of a BuOrd Mark 12, 400-cycle servomotor is approximately 24 radians per second. The added inertia required by the specifications plus the motor characteristics make the natural frequency of the mechanical system approximately eight radians per second. The addition of the tachometer in a feedback loop as shown in figure 5 will increase the natural frequency of the output member to approximately 60 radians per second. This natural frequency, $1/T_m$, is of the proper magnitude to give a well-damped, complete system with a bandwidth of 20 radians per second when the integrator time constant is made large enough.

## Integrator

12. The block diagram of the integrator is shown in figure 6. The over-all transfer function of this circuit is (see reference 1):

$$\frac{E_o}{E_i} = \frac{K_D(TJ\omega+1)}{TJ\omega} \qquad \text{Eq. (6)}$$

when the gain

$$abK_D = 1 \qquad \text{Eq. (7)}$$

(See figure 6 for definition of a, b, and T.)

The gain $K_D$ is the d-c gain of the amplifier (d-c volts out divided by d-c volts in).

13. When the integrator of figure 5 is used with the output member described above, the integrator time constant must be 0.167 second for the maximum phase margin of the complete system to occur at the specified bandwidth of 20 radians per second. For these values the maximum phase margin is 55 degrees. A phase margin of 45 degrees gives a well stabilized system; therefore, the above system could have the loop closed anywhere from 8 to 50 radians per second. An increase in integrator time constant will make the system more stable at the maximum phase margin and increase the range of frequencies over which the system will be stable.

## Complete System

14. The circuit diagram of the complete system showing parameter values external to the amplifier is shown in figure 7. The parameter values were set approximately by the above techniques and then readjusted experimentally for optimum performance with the mark 12 motor. The only essential change was in the integrator time constant which was increased from 0.167 second to 0.250 second.

15. A Mark 16 motor was substituted for the Mark 12 motor and the system characteristics were essentially unchanged. The system still met all the dynamic specifications and was stable. The closed-loop, frequency-response curves of the system using both motors are shown in figure 8. The curves show that the magnetic control amplifier XM-13A works equally well with either the Mark 12 or Mark 16 motor.

## Conclusions

16. The characteristics of the XM-13A magnetic control amplifier with the simulated load, given in Table I, are well within the performance characteristics required.

17. The advantages of this control amplifier, in addition to those inherent in magnetic amplifiers in general, are twofold. Mark 12 and Mark 16 motors are interchangeable when this control amplifier is used, and all the cores used in this amplifier are the same size with the same windings. These advantages are mainly from a production standpoint.

18. The engineering of this control amplifier to meet the AN-E-19 temperature, voltage, and frequency specifications is a matter of properly selecting and matching components. The extent and complexity of the matching and selecting procedure must be determined experimentally.

## Acknowledgment

The men who, in addition to the author, completed the design and construction of this control amplifier were Mr. C. M. Davis, Jr. and Mr. C. V. Thrower of the Magnetic Amplifier and Servomechanisms Section of the Magnetics Division.

TABLE I

| | Required Specifications | XM-13A Specifications |
|---|---|---|
| Size | 8 1/4" x 2 1/4" x 4 3/4" | 6 1/2" x 2 1/4" x 4 3/4" |
| Static Error | 0.05 degree | 0.03 degree |
| Dynamic Error at 20 deg./sec. | 0.10 degree | 0.05 degree |
| System Bandwidth | 3 cycles/sec. | 4 cycles/sec. |

## REFERENCES

1. H. H. Woodson, "Magnetic Amplifier Servo Compensation," Navord Report 2709, Naval Ordnance Laboratory, White Oak, Maryland; January 1953.

2. C. W. Lufcy, A. E. Schmid, P. W. Barnhart, "An Improved Magnetic Servo Amplifier," AIEE Technical Paper 52-235.

3. W. R. Ahrendt and J. F. Taplin, "Automatic Feedback Control," McGraw-Hill Book Company, Inc., New York; 1951.

4. C. W. Lufcy, et al., op. cit.

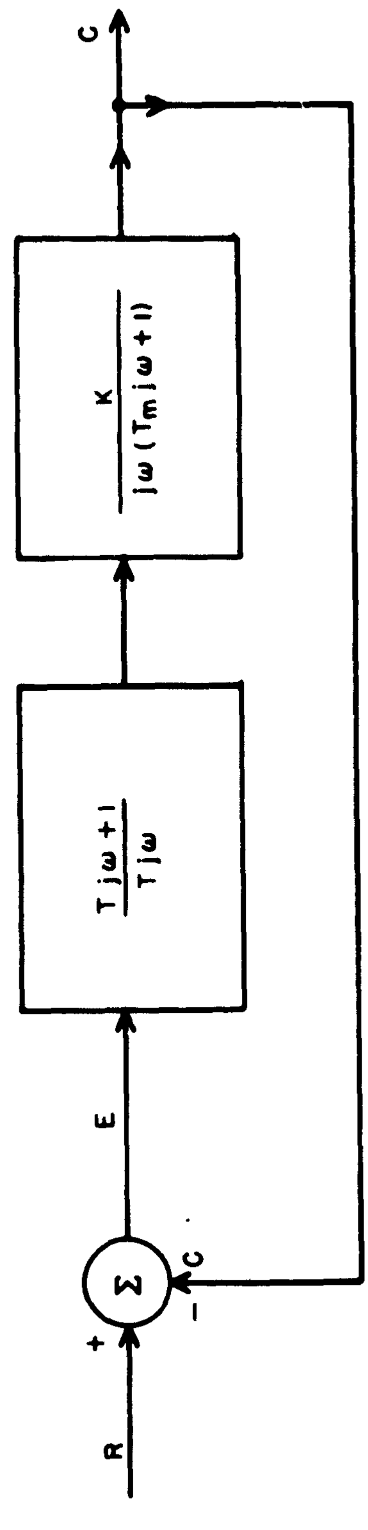



FIG. I

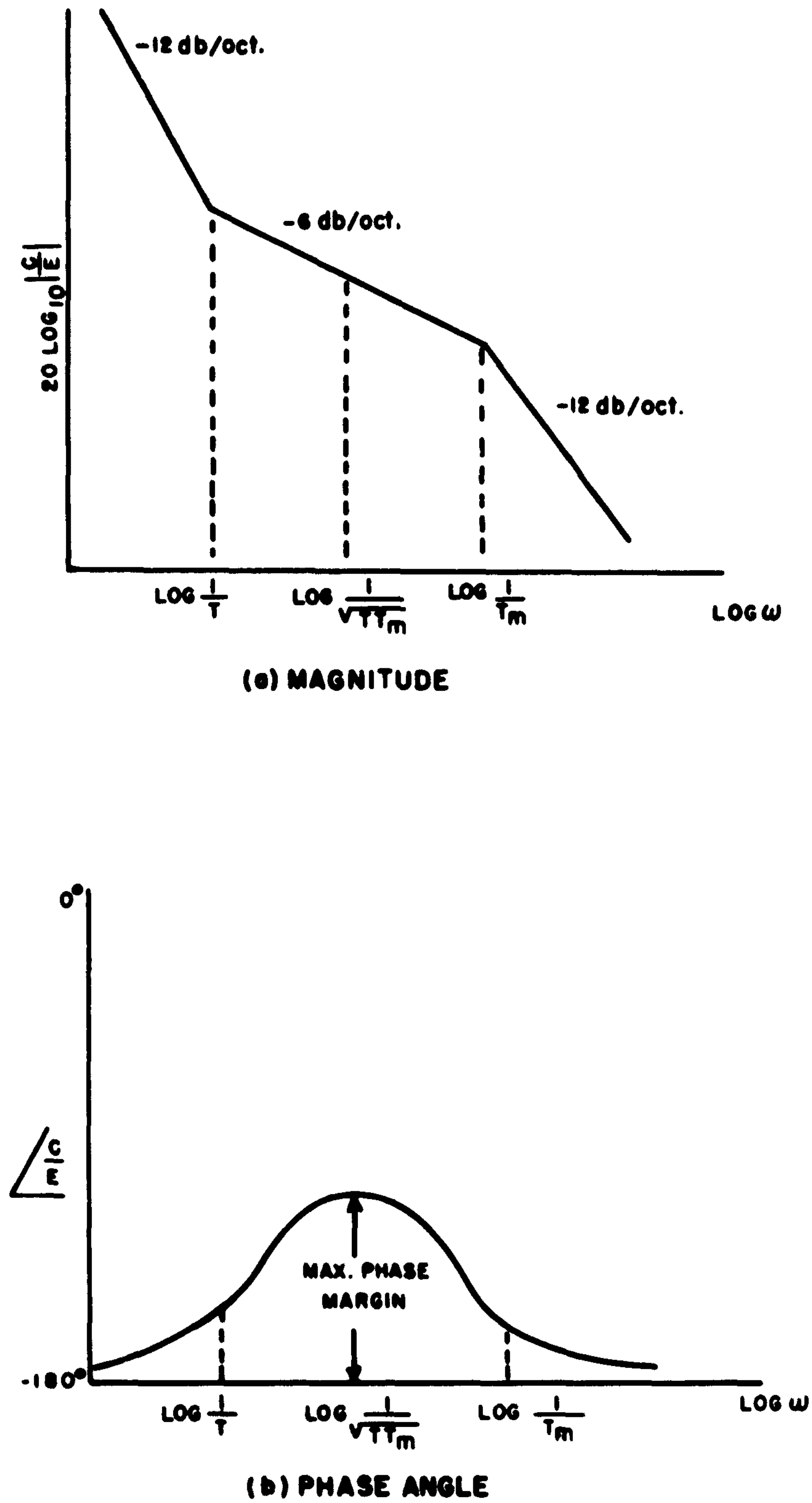

-12 db/oct.
-6 db/oct.
-12 db/oct.
20 LOG10 |C/E|
LOG 1/T
LOG 1/√TTm
LOG 1/Tm
LOG ω
(a) MAGNITUDE
0°
∠C/E
MAX. PHASE MARGIN
-180°
LOG 1/T
LOG 1/√TTm
LOG 1/Tm
LOG ω
(b) PHASE ANGLE

FIG. 2

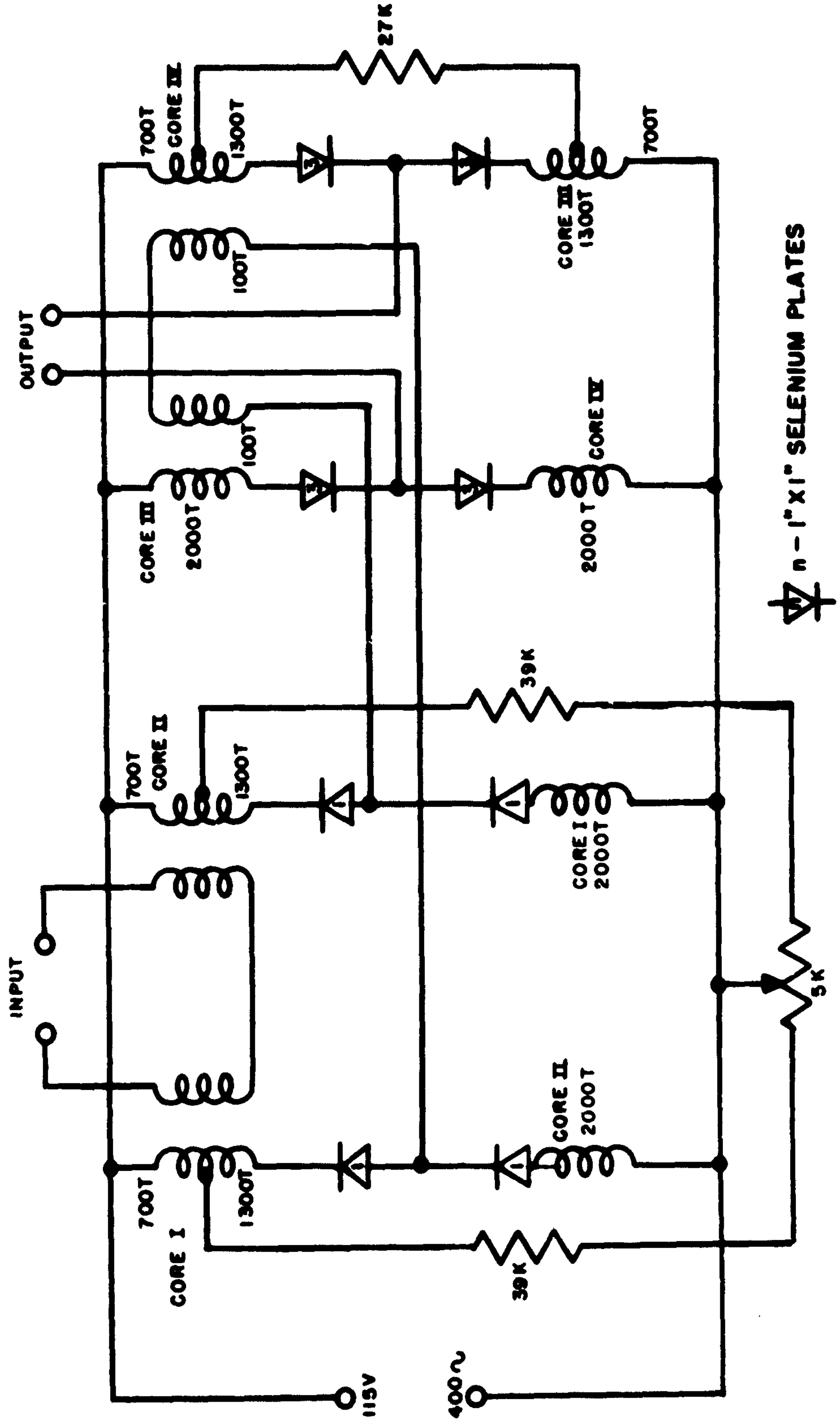
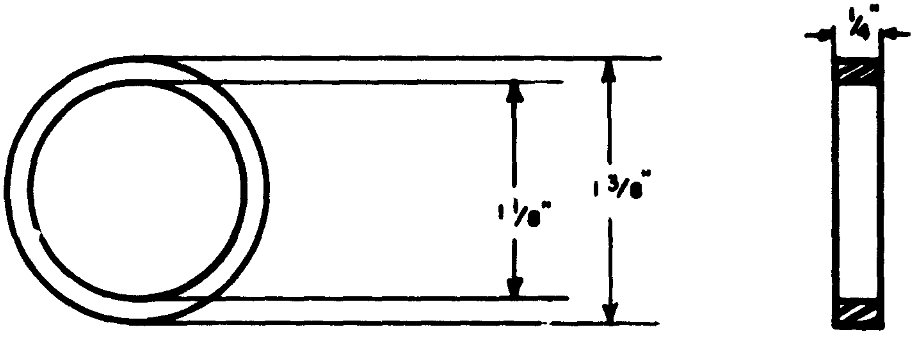

27K
700T
1300T
100T
OUTPUT
CORE III
2000T
CORE IV
2000 T
n-1"X1" SELENIUM PLATES
39K
700T
CORE II
1300T
CORE I
2000T
INPUT
5K
CORE II
2000T
700T
1300T
CORE I
39K
115V
400~

FIG. 3

DETAILS OF MAGNETIC CORES




MATERIAL: 50%Ni/50%Fe ALLOY, GRAIN-ORIENTED
DRY HYDROGEN ANNEAL
CONFIGURATION: TAPE-WOUND TOROID
TAPE THICKNESS: 0.002 inches
INSULATION: MgO APPLIED IN WINDING PROCESS

WINDINGS

| FUNCTION | TURNS | TAPS | WIRE SIZE |
|---|---|---|---|
| POWER | 2000 | | #31 |
| POWER | 2000 | 700 | #31 |
| CONTROL | 1000 | 100 | #36 |

FIG. 4

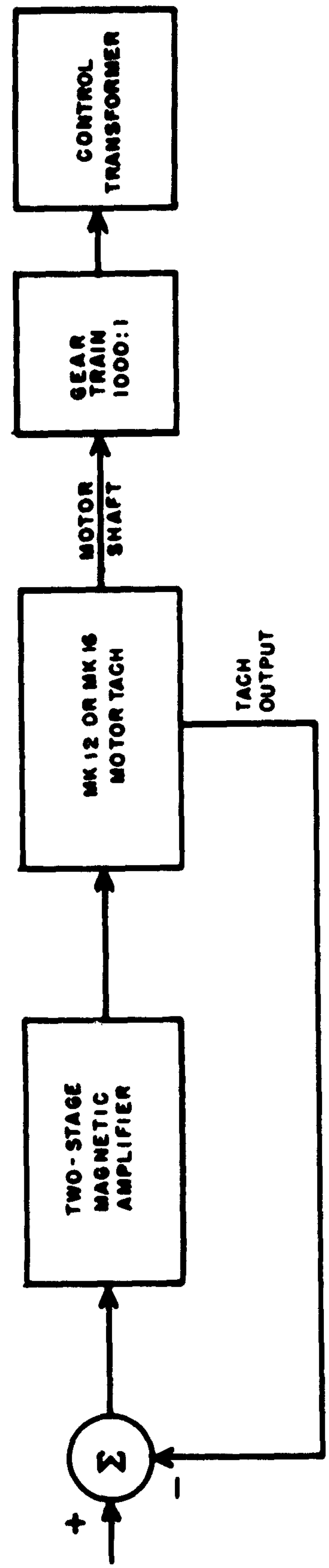

CONTROL TRANSFORMER
GEAR TRAIN 1000:1
MOTOR SHAFT
MK 12 OR MK 16 MOTOR TACH
TACH OUTPUT
TWO-STAGE MAGNETIC AMPLIFIER
Σ
+
-

FIG. 5

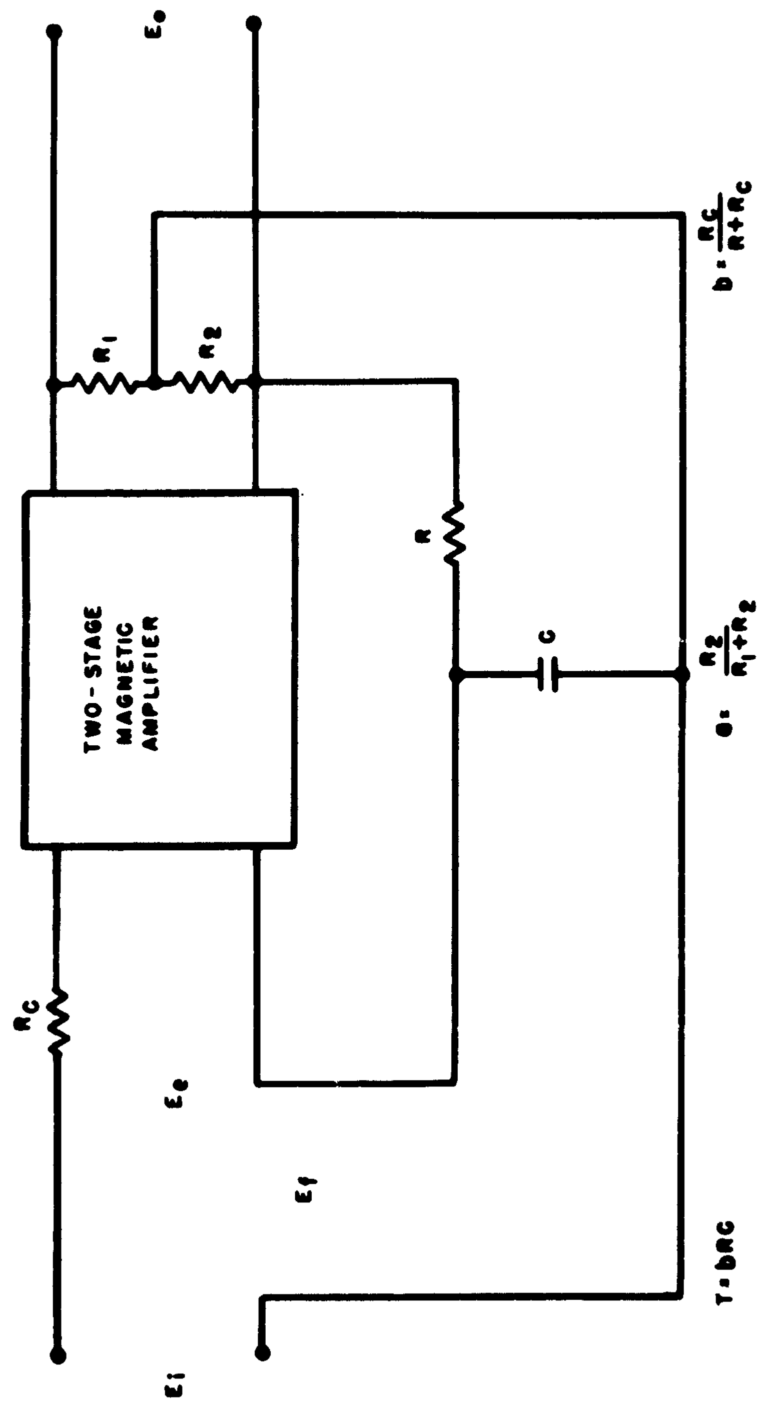

TWO-STAGE MAGNETIC AMPLIFIER
$E_o$
$R_1$
$R_2$
$R$
$C$
$R_C$
$E_e$
$E_f$
$E_i$
$b = \frac{RC}{R+RC}$
$a = \frac{R_2}{R_1+R_2}$
$T = bRC$

FIG. 6

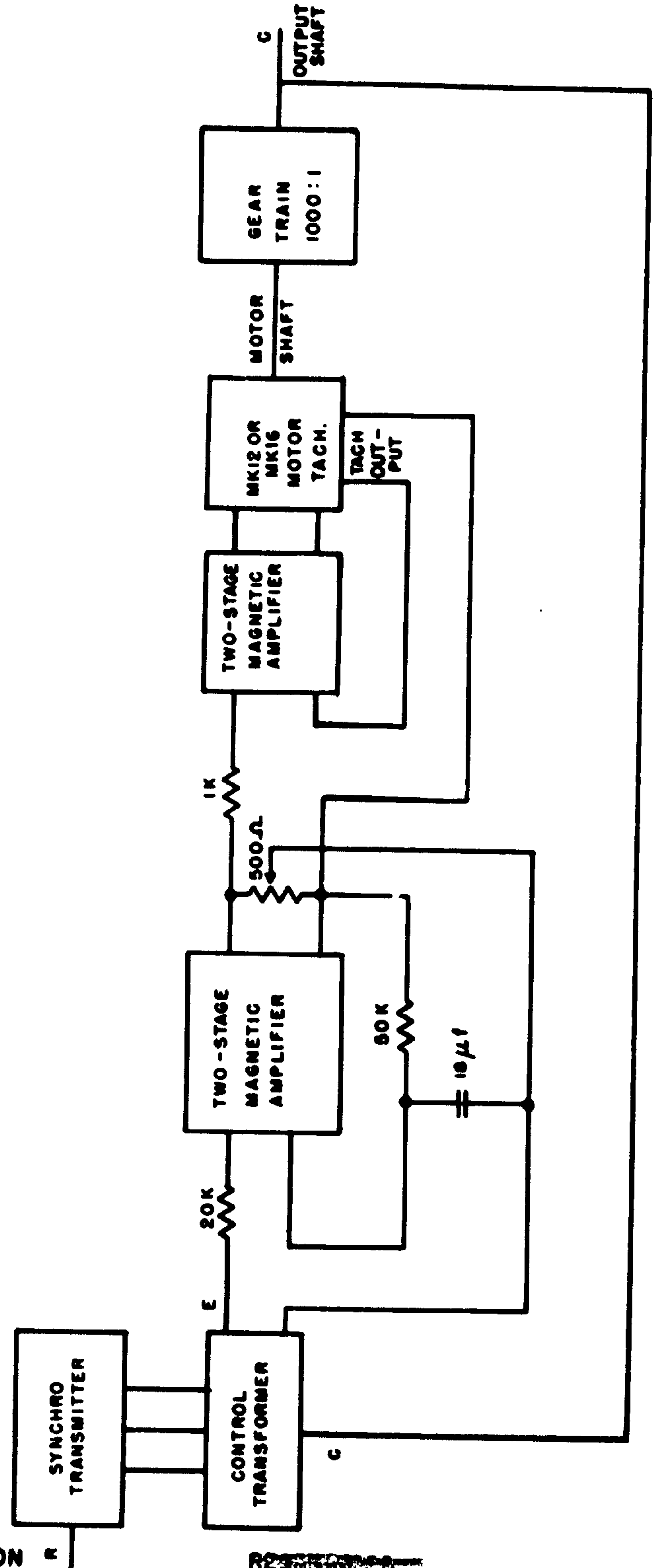

SYNCHRO TRANSMITTER
CONTROL TRANSFORMER
R
E
C
20K
TWO-STAGE MAGNETIC AMPLIFIER
80K
16 μf
500Ω
1K
TWO-STAGE MAGNETIC AMPLIFIER
MK12 OR MK16 MOTOR TACH.
TACH OUT-PUT
MOTOR SHAFT
GEAR TRAIN 1000:1
OUTPUT SHAFT
C

FIG. 7

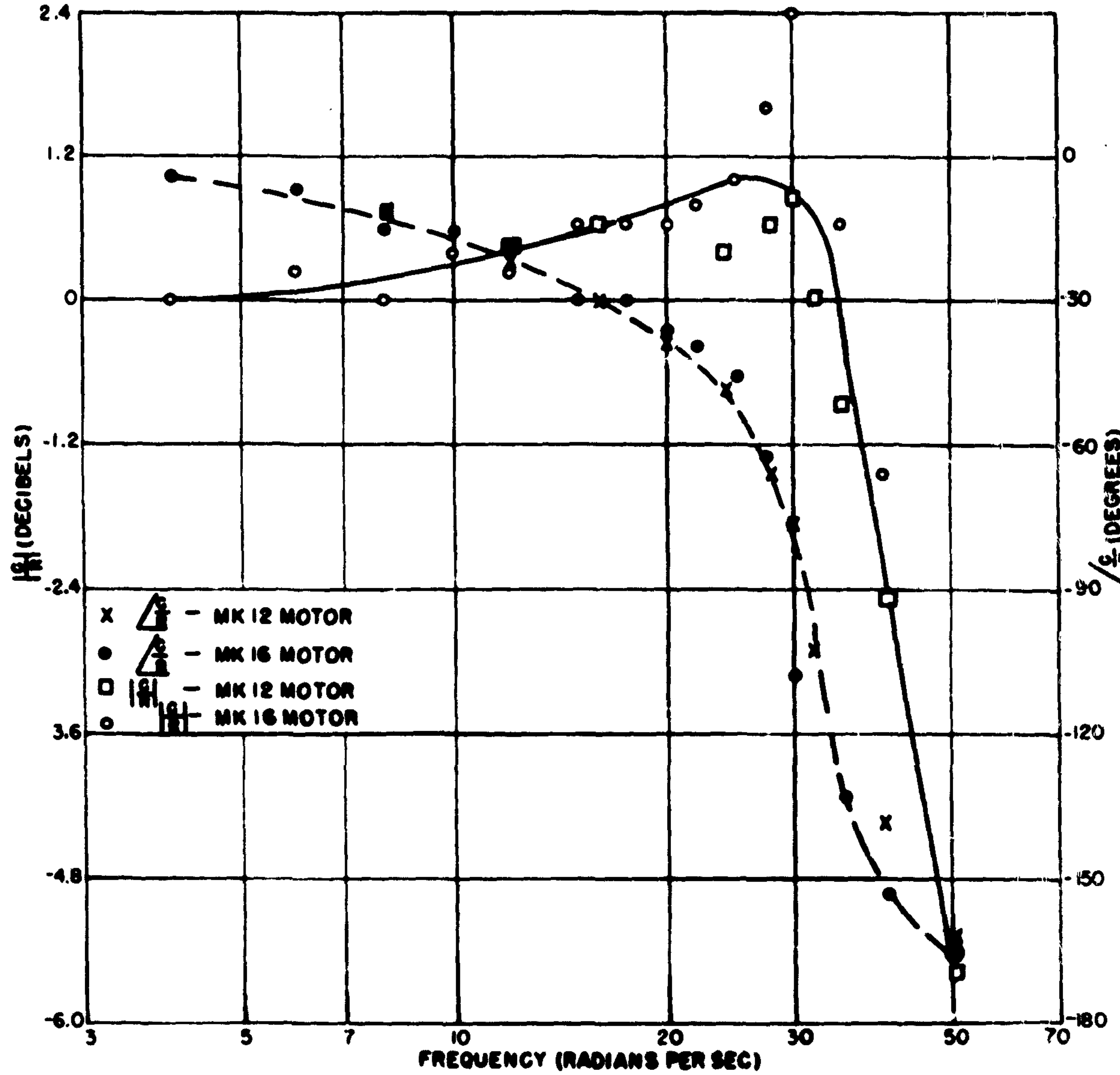

2.4
1.2
0
-1.2
-2.4
3.6
-4.8
-6.0
0
30
60
90
120
150
180
3
5
7
10
20
30
50
70
FREQUENCY (RADIANS PER SEC)
|C/R| (DECIBELS)
∠C/R (DEGREES)
X ∠C/R - MK 12 MOTOR
● ∠C/R - MK 16 MOTOR
□ |C/R| - MK 12 MOTOR
○ |C/R| - MK 16 MOTOR

FIG. 8